

NPS ARCHIVE
1962
GERONIME, E.

A DIGITAL-ANALOG COMPUTER FOR USE IN
AERODYNAMIC HEAT SIMULATION SYSTEM

EUGENE LEO GERONIME

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY CA 93943-5101

A DIGITAL-ANALOG COMPUTER CONTROL FOR USE IN
AN AERODYNAMIC HEAT SIMULATION SYSTEM

A THESIS
SUBMITTED TO THE DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
AND THE COMMITTEE ON GRADUATE STUDY OF
STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
ENGINEER



By
Eugene Leo Geronime

August 1962

Wl

ACKNOWLEDGMENT

The author wishes to gratefully acknowledge the guidance, encouragement, and constructive criticism given by Professor W. H. Horton in the writing of this thesis.

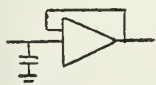
TABLE OF CONTENTS

	Page
Acknowledgment	iii
List of symbols	v
I Summary and introduction	1
II Basic logic and block diagram	3
III Component design evaluation.	6
IV Overall system engineering and performance	8
V Conclusions.	10
References	15
Appendices	
A Basic analog computer techniques	A-1
B Radiant heating facility	B-1
C Test data.	C-1

LIST OF SYMBOLS

$C_{1 \rightarrow 4}$	Capacitors for the storage of the desired heat flow signal
C_{qr}	Capacitor for the storage of the radiant heat flow signal
C_{T_1}	Capacitor for the storage of the adiabatic wall temperature signal
C	Control voltage analogous to $(q_d - q_m)$
h	Coefficient of heat transfer (BTU/hr/ft ² /°F)
K_1	Stefan Constant (BTU/hr/ft ² /°F ⁴ abs)
K_2	Thermal conductivity (BTU/ft ² /°F)
M	Amplifier gain
q	Convective heat flow (BTU/hr/ft ²)
q_r	Radiant heat flow (BTU/hr/ft ²)
q_d	$q + q_r =$ desired heat flow (BTU/hr/ft ²)
R	Resistor (ohms)
R_f	Feedback Resistor
t_{aw}	Adiabatic wall temperature (°F abs)
t_s	Surface temperature (°F abs)
t	Time

 High gain operational amplifier

 Operational amplifier used as a peak follower

 Operational amplifier with feedback

V_o Output voltage

V_i Input voltage

I. SUMMARY AND INTRODUCTION

During the past decade aircraft speeds have extended further and further into the supersonic regime. Today, most aircraft design companies project civil transports to fly between Mach 2 and Mach 3. Such machines will experience structural problems due to the aerodynamic heating associated with these high speeds. Therefore there is a need for structural research into the effects of this type of environment. Early studies on radiant heat techniques for thermal simulation were made by Abramson in the United States and Horton^{[1,2,3,4,5]*} in Great Britain concurrently. Their works proposed computer controlled systems using quartz tubular heaters as the basic heat producing elements. The concept of a time-shared computer for the calculation of desired radiant heat flow was described by Horton^[5]. The idea has been amplified and enlarged in this work.

A practical aerodynamic heating computer-controller must be:

- (1) Capable of producing the correct temperatures over a given range of Mach numbers.
- (2) Relatively simple to operate.
- (3) Dependable.
- (4) Safe to operate.
- (5) As inexpensive as possible.

To create the thermal environment corresponding to a given Mach number, the simulator must produce the appropriate heat flow. This has three components.

- (1) The convective heat transfer to the body.
- (2) The radiant heat transfer to or from the body.
- (3) The internal heat generated within the body.

* Superscript numerals in brackets refer to the References at the end of the report.

It is normally accepted that the Newtonian law can be used to compute the convective heat flow.^[6] Thus, the convective heat input condition is defined by

$$q = h(t_{aw} - t_s)$$

where:

q = heat flow per unit area (BTU/ft²)

h = heat transfer coefficient (BTU/hr/ft²/°F)

t_{aw} = adiabatic wall temperature (°F abs)

t_s = surface temperature (°F abs)

The purpose of this work was to design and build a control system to meet the above conditions. Even though the equipment is the result of a university research project, it is felt that many of the ideas developed are directly applicable to industrial plants.

The results of the investigation show that the use of a time-shared, digital-analog computer control is feasible and most desirable from a standpoint of cost, accuracy, simplicity and dependability. Although the control was limited to a four channel heating system, the results show that it is possible to expand the system to more channels, and to include loading should this be desired.

II. BASIC LOGIC AND BLOCK DIAGRAM

As stated previously the accepted Newtonian equation:

$$q = h(t_{aw} - t_s)$$

was used to determine the desired convective heat flow, q , into the body. External radiant heat input, q_r (such as from a bomb flash or solar radiation) was considered to be a quantity which could be positively defined and supplied as an analog from a function generator. (In fact, the basic digital to analog converter was adapted for this purpose.) Radiant heat loss in flight was considered as a correction term to the q supplied, since the computation $K_1 t_s^4$ and the computation

$$K_2 \frac{\partial t_s}{\partial t}$$

are closely allied.

The quantities t_{aw} , h , and q_r can, for any specific flight program, be defined explicitly as time dependent variables. Therefore analogous time dependent voltages can be produced from appropriate function generators. However, it is our premise that if the operations involving t_{aw} , h , and q_r can be sequentially programmed, then a single digital to analog converter can be adapted to generate all. (See Fig. 1) In the system developed, a tape reader is used to set up a voltage analogous to q_r at time t in the program. This voltage is stored in a simple capacitor store using a peak follower circuit as described later. Next, at the time $t + \Delta t$ the adiabatic wall temperature, t_{aw} , is generated. The appropriate surface temperature, t_s is measured by a thermocouple^[7] and is combined with t_{aw} in a summation circuit described in Section III. The output from the summer is stored and when the tape advances to read the heat transfer coefficient, the stored temperature potential is fed into the converter as a reference voltage. The converter then multiplies the temperature potential by the heat transfer coefficient, thus computing q . At the same time q_r , previously stored, is added to q giving a voltage analogous to the desired heat flow, q_d , uncorrected for radiant loss. The signal is

fed into a comparator where it is compared with the measured heat flow corrected for radiant loss. The difference, C , between the computed and measured values is used to adjust the output of the saturable core reactors so that C converges to the control point for correct heat flow. Details of the comparison system, the saturable core reactor control, and the heat input determination are given in Ref. [8] and [9] respectively.

The basic logic shown in the block diagram (Fig. 1) was used in the design of the control system discussed. In order to satisfy the design requirements as previously stated, the system incorporates time sharing and digital to analog conversion techniques. Figure 2 is a diagram of the time-shared computer control system. In order to familiarize the reader with its operation, the time-wise sequence of events required to compute q_d , will be followed.

(The system components are described in Section III, and Appendix A contains basic analog computer techniques.^[10])

First, assume the wipers are on pole one of each of the nine banks and the tape input command is q_r . The reader generates a voltage proportional to q_r from the reference voltage and this is fed through pole one of bank one to the storage capacitor C_{qr} . The switch is now stepped to position two and the tape command is simultaneously changed to t_{aw} . The reader generates a voltage analogous to t_{aw} from the original reference voltage. t_{aw} , as a voltage, passes through pole two of bank one to the storage capacitor C_{t1} . The output of peak follower two is analogous to t_{aw} and, via summer four, has t_s subtracted. This quantity, $-(t_{aw} - t_s)$, is now an analog signal appearing at pole three of bank one. Once again the switch advances and the tape command changes to h . The analogous voltage to $-(t_{aw} - t_s)$ appears as a reference voltage and is multiplied by the command signal in the reader head giving q . At the same time, q_r is added to q in amplifier one giving the analogous voltage of q_{d1} . This voltage passes through pole three of bank six, seven, and eight; and is stored in C_{1a} and C_1 . The output of peak follower six is a continuous voltage analogous to q_{d1} . As the steps continue, channels two, three, and four are filled in order.

Banks four and five are used to empty the storage capacitors in order to allow the storage of decreasing voltages.

Banks seven and eight isolate C_1 . This is necessary in order to prevent discontinuous signals of q_d and still allow for decreasing voltage levels analogous to desired heat flow.

III. COMPONENT DESIGN EVALUATION

An eight pin Soroban tape reader is utilized in the function generator section of the control system. The reader is used to connect various combinations of resistors to amplifier one. As shown in Appendix A, the output voltage of a summer amplifier is:

$$V_o = - \left(\frac{R_f}{R_1} + \frac{R_f}{R_2} + \frac{R_f}{R_3} + \dots \right) V_i$$

Therefore, by proper choice of resistor values, and by correct choice of hole combinations in the tape, the reader head in conjunction with amplifier one, will produce any multiple of a given voltage. The principle of this operation is illustrated in Fig. 3, a simplified diagram of the reader head amplifier combination. The choice of the resistors was made to correspond with the values of numbers on a Soroban tape puncher used in programming. Since the tape puncher keyboard is limited to numbers from 1 to 159, the maximum inaccuracy of generation is

$$\pm \frac{X}{2(159)}$$

where X is the operating reference voltage range. If full utilization of the eight holes had been made in the tape puncher, 255 combinations would result, with a maximum inaccuracy of

$$\pm \frac{X}{2(255)}$$

Therefore, unless conformity to available equipment is a criteria, any accuracy desired may be obtained, since the inaccuracy is equal to

$$\pm \frac{X}{2(2^n - 1)}$$

where n is the number of holes.

Amplifiers used in the digital-analog computer control are Model K2-XA operational amplifiers made by Philbrick Researches Incorporated. The K2-XA has a small signal rise time of 1 μ sec, an input impedance

of over 100 Meg Ω , output range of ± 100 v , and a drift rate referred to the input of approximately 8 mv per day.

Amplifier 3, Fig. 2, is a chopper stabilized amplifier with a DC gain of 1000. This amplifier uses a Philbrick K2-P stabilizing amplifier in conjunction with a K2-XA in order to increase stability, giving it a long term drift rate of less than 0.1 mv/day referred to the input.

The peak follower circuit mentioned previously is simply a K2-XA amplifier with a feedback loop of zero resistance. A capacitor, isolated from the rest of the circuit by a diode and the amplifier, is charged to the peak value of the input signal. The amplifier output produces a continuous voltage equal to the charge on the capacitor. Discharge time constants of five minutes or longer are obtainable.

Multi-contact rotary stepping switches were used in the control system. Four milliseconds switching time is required with a self-excited stepping capability of 58 steps per second. The electrical noise resulting from the use of the stepping switch was not a problem since signal voltages were kept large whenever possible to completely overshadow the microvolt noise level.^[11] Also, the reader delays inputs until after all wipers have attained their new positions.

A Philbrick dual power supply, Model R-100B was used to drive all the operational amplifiers. Typical drift for this power supply is less than 100 mvdc per day.

The storage of voltages in the control system is done entirely by the use of capacitors. C_{tl} and C_{qr} shown in Fig. 2 are 0.5 μ f while the rest of the storage capacitors are 0.25 μ f . The charging time of the capacitors is ten milliseconds. After this period, the capacitors have attained 99.9% of their final charge. The charging time of 10msec would permit switching up to sixty steps per second. The speed in this control system was limited to ten steps per second by the motor drive on the reader head. Time base for the entire control system was generated by an adjustable pulsing circuit shown in Fig. 4. This pulse was used to synchronously step the reader head and switches.

IV. OVERALL SYSTEM ENGINEERING AND PERFORMANCE

The four channel control system performance data is found in Appendix C. Tests were run to determine the accuracy and repeatability of multiplication by the computing system. Since accuracy of computation is directly effected by the peak follower output; determination of the R-C time constants for the storage network was also made.

Accuracy of multiplication was found to be in error by 1.6% or less for computing speeds of eight steps per second. This accuracy was determined by multiplying two known reference voltages together, measuring the product and comparing it with the otherwise calculated value. (see Appendix C)

Because of the inherent stability of the computer components and care taken in wiring to guard against ground loop problems, the repeatability of computation over a fifteen minute period resulted in output variations of less than 1.0%.

R-C time constants for the peak follower inputs were found to be five minutes or greater resulting in peak follower output variations of less than 0.5% for a switching time of 0.12 seconds.

Accuracy of producing q_r , h , and t_{aw} is dependent upon the number of discrete levels of the reader, the tolerances of the resistors used, and the accuracy of the reference voltage. First, 159 numbers were available giving the reader a maximum inaccuracy of 0.3%. The reference voltage was a dry cell, and since the current demand was at most a few microamperes, it was considered to have constant output. Finally, the measured error due to resistor tolerance was $\pm 3\%$ maximum.

As stated previously, maximum switching speed was limited to 10 cycles per second by the motor drive on the reader head. Since three steps are necessary for each determination of q_d , corrected outputs of desired heat flow were made every 1.2 seconds for each of the four channels. This speed could have been increased by a factor of five simply by changing the motor speed without adversely effecting the accuracy of the control system.

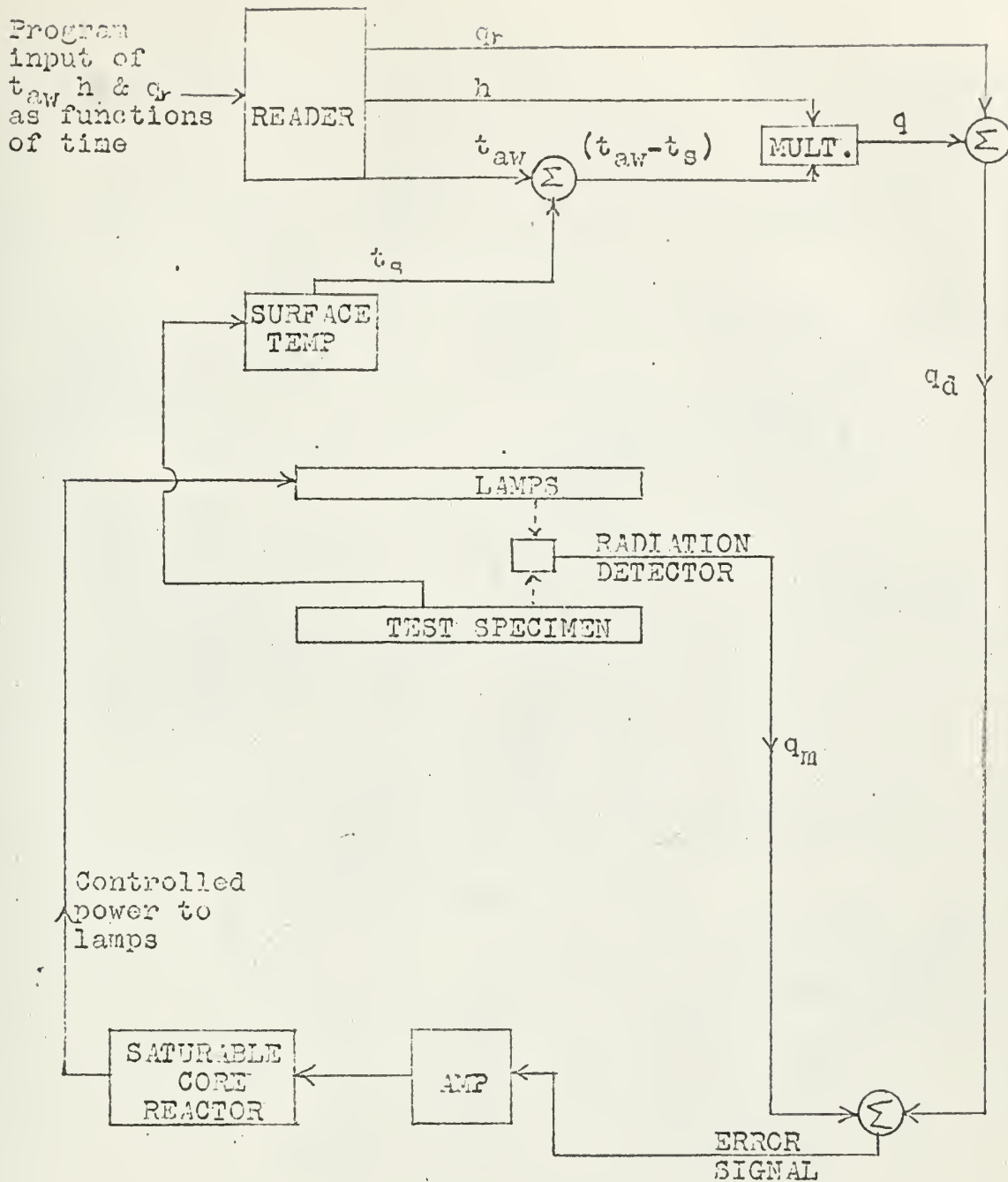
Total cost of the control system described in this work was approximately \$1,500.

To prevent the hazards of infra red radiation exposure to operating personnel, the control system and instrumentation was remotely located in a room overlooking the test sight. A description of the facility layout is given in Appendix B.

V. CONCLUSIONS

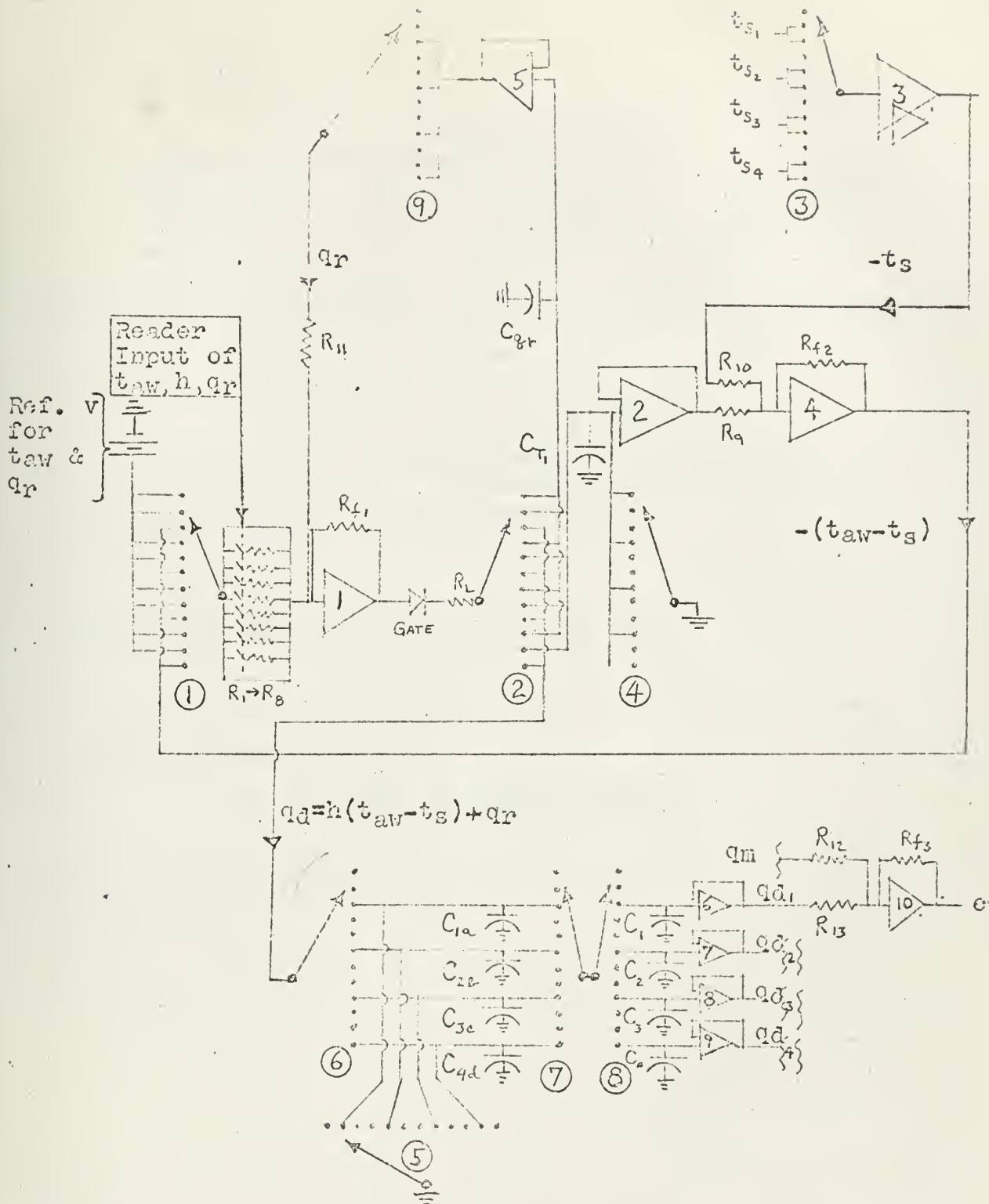
From the results of this investigation it is concluded that a time-shared digital-analog computer control system for aerodynamic heating is

- (1) capable of heat simulation control up to Mach 6.
- (2) simple.
- (3) dependable.
- (4) safe to operate.
- (5) relatively inexpensive.



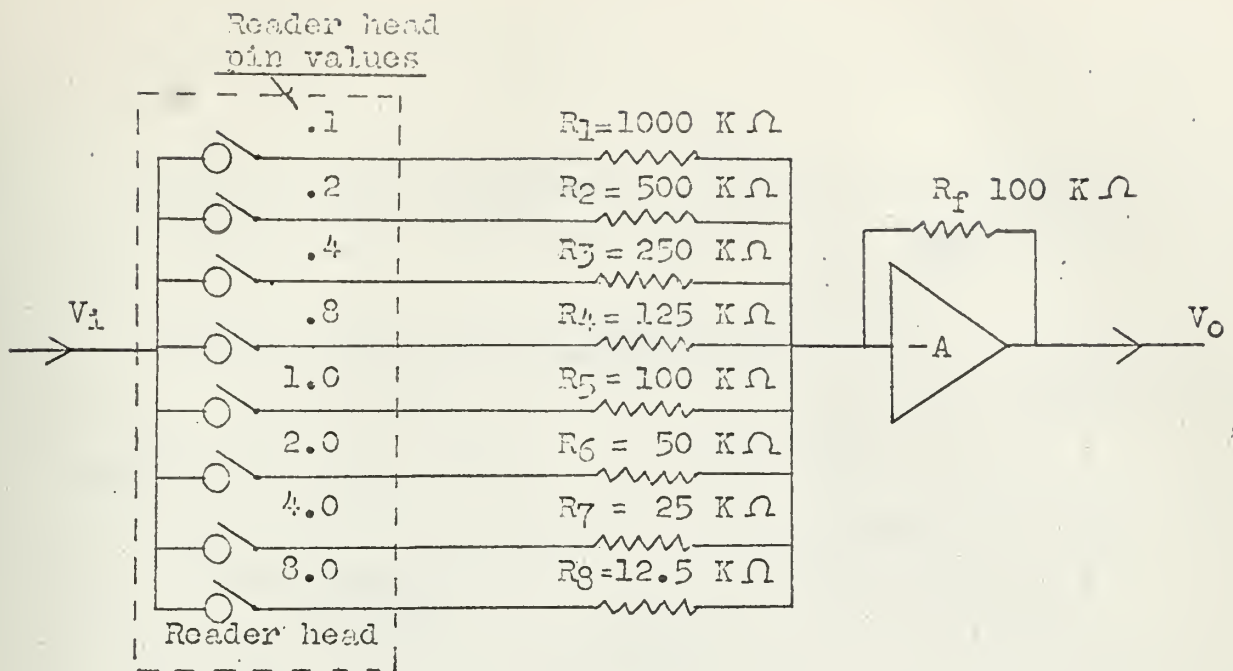
Block Diagram of a Closed Loop Control System for the Simulation of Kinetic Heating

Fig. 1



Schematic Diagram of a Time Shared System for the Determination of " q_d "

Fig. 2



Example of multiplication of V_i by 11.7

Reader switches 8.0, 2.0, 1.0, .4, .2, and .1 are closed. Therefore;

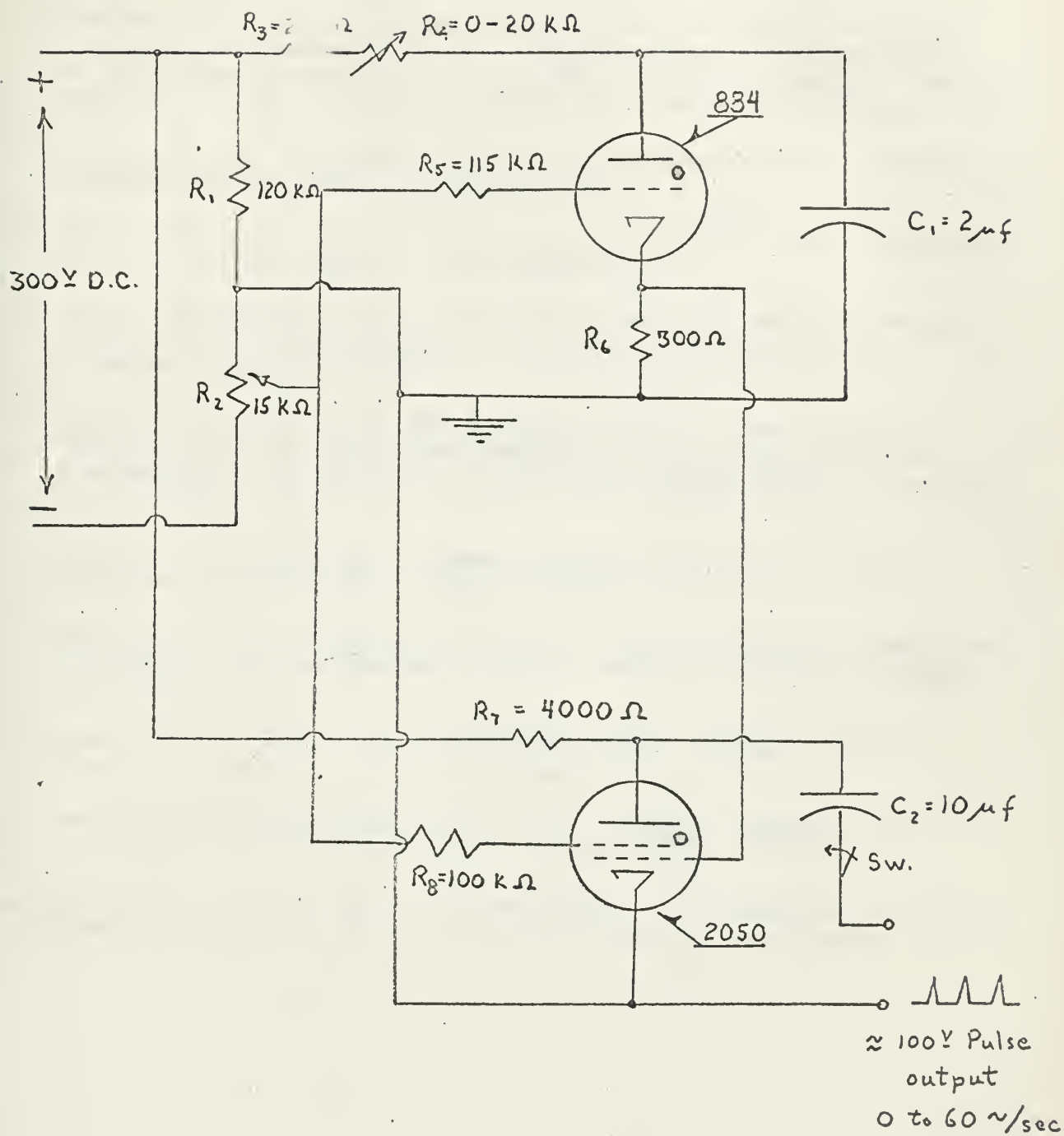
$$V_o = -\left(\frac{R_f}{R_8} + \frac{R_f}{R_6} + \frac{R_f}{R_5} + \frac{R_f}{R_3} + \frac{R_f}{R_2} + \frac{R_f}{R_1}\right) V_i$$

or substituting values gives

$$V_o = -11.7 V_i$$

Diagram of Control System Multiplication Stage

Fig. 3



Circuit Diagram of a Time Base Pulse Generator

Fig. 4

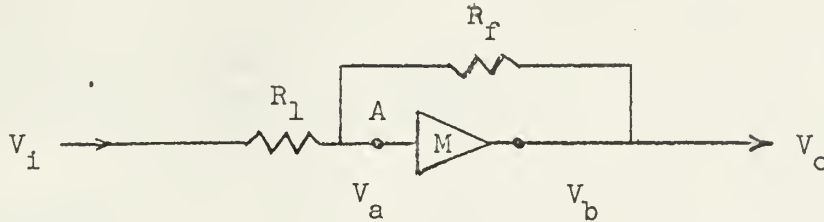
REFERENCES

1. Horton, W. H., "The Simulation of Aerodynamic Heating in Full Scale Tests of Aircraft Structures", R.A.E. Tech. Note Structures 175, August 1955.
2. Horton, W. H., "The Influence of Kinetic Heating on the Design and Testing of Aircraft Structures", 1955 Proceedings of the Conference on High-Speed Aeronautics, Editors: Antonio Ferri, Nicholas J. Hoff, and Paul A. Libby, Polytechnic Institute of Brooklyn, Brooklyn, N. Y.
3. Horton, W. H., "Laboratory Simulation of Kenetic Heating", Aircraft Engineering, Vol. XXVI, No. 303, May 1954.
4. Horton, W. H., "Experimental Methods in Kinetic Heat Tests", Aircraft Engineering, Vol. XXIX, No. 342, August 1957.
5. Horton, Wilfred Henry, The Simulation of Heat and Load Environment in High Speed Vehicles, Engineers Thesis, Stanford University, Stanford, California, 1959.
6. Loria, J. C., Mar, J. W., and Blackstock, W. J., "The design and Application of the MIT Radiant Heating Structural Test Facilities", Proceedings of the Society for Experimental Stress Analysis, Vol. XV, No. 1, 1957.
7. White, F. J., "Accuracy of Thermocouples in Radiant Heat Testing", Experimental Mechanics, pp. 204, July 1962.
8. Campbell, J. D., A Feedback System for Automatic Control of Simulated Aerodynamic Heating, Engineers Thesis, Stanford University, Stanford, California, 1962.
9. Watson, R. M., A Heat Flow Measurement System, Engineers Thesis, Stanford University, Stanford, California, 1962.
10. Wass, C.A.A., Introduction to Electronic Analogue Computers, Sec. Revised Ed., Pergaman Press, Ltd., England, 1956.
11. Keister, W., Ritchie, A. E., and Washburn, S. H., Design of Switching Circuits, D. Van Norstand Co., Inc., Toronto, New York, London, 1951.

APPENDIX A

Analog Summation

The operational amplifier used in the summation circuit has an input impedance which is assumed to be infinitely large.



Since the input impedance is infinite, the current through terminal A is zero and currents through R_l and R_f are equal. The following equation may be written:

$$\frac{V_i - V_a}{R_l} - \frac{V_a - V_o}{R_f} = 0 \quad (1)$$

also

$$V_o = -M V_a \quad (2)$$

Eliminating V_a from equations (1) and (2) gives:

$$R_f \left(V_i - \frac{V_o}{M} \right) = -R_l \left(V_o + \frac{V_o}{M} \right) \quad (3)$$

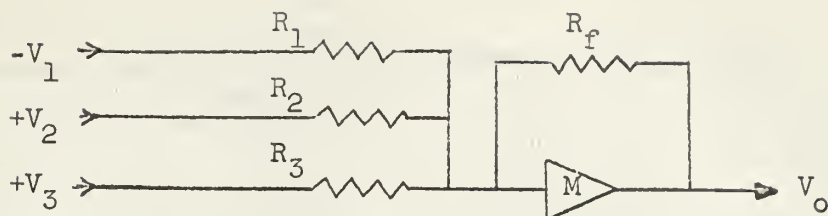
or rewriting

$$\frac{V_o}{V_i} = - \frac{R_f M}{R_f + R_l(1 + M)} \quad (3a)$$

If M is very large, the approximation is made:

$$V_o \cong - \frac{R_f}{R_l} V_i \quad (4)$$

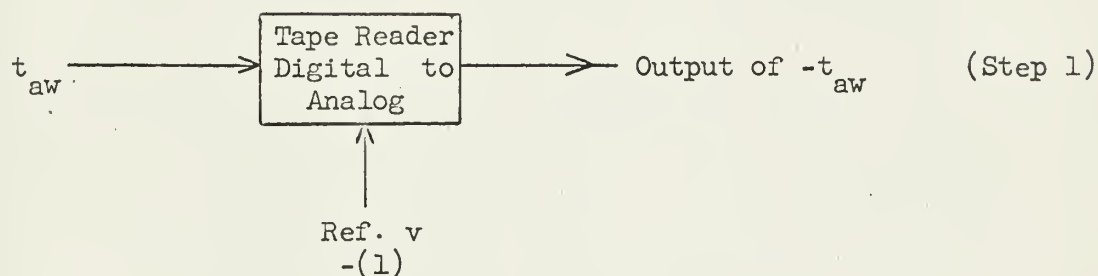
For several inputs this can be extended.



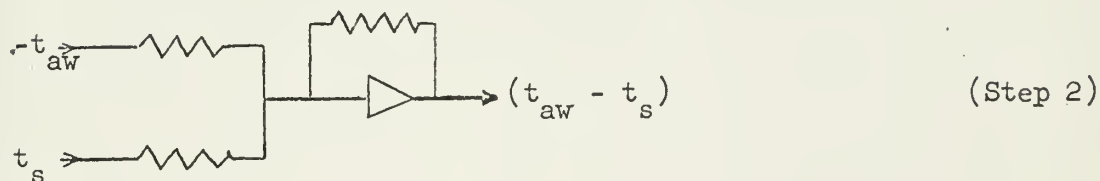
$$V_o = \left(\frac{R_f}{R_1}\right) V_1 - \left(\frac{R_f}{R_2}\right) V_2 - \left(\frac{R_f}{R_3}\right) V_3 \quad (5)$$

Multiplication

t_{aw} is generated as a voltage signal by multiplying it by a reference voltage.



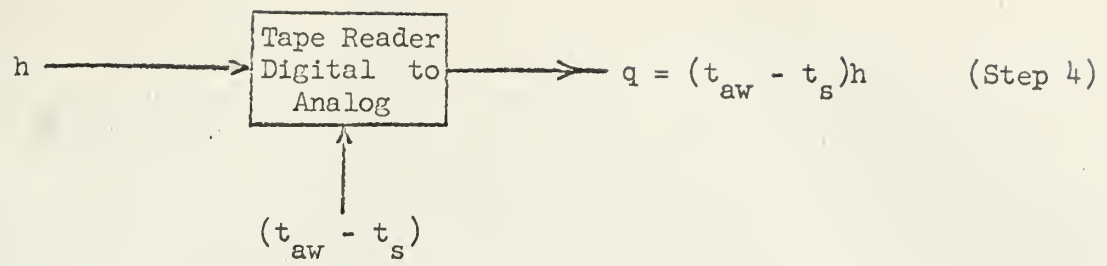
t_s is added to $-t_{aw}$ in a summer (See equation 5) to give $(t_{aw} - t_s)$.



The analogous voltage, $(t_{aw} - t_s)$, is stored in a capacitor and appears as a continuous output of a peak follower.



The output of the peak follower is fed back to the tape reader as a reference voltage where it multiplies h to give q .



APPENDIX B

STANFORD UNIVERSITY RADIANT HEATING
STRUCTURAL TEST FACILITY

by

John D. Campbell
Eugene L. Geronime
Robert M. Watson

APPENDIX B: STANFORD UNIVERSITY RADIANT HEATING STRUCTURAL TEST FACILITY

I. INTRODUCTION

The need for aerodynamic heat simulation in structural testing of supersonic aircraft is well recognized. Thus, the authors undertook the design and construction of a four channel radiant heating test facility at Stanford University during the summer of 1962. The system was designed to meet the following requirements: a high intensity, rapid response heat source; an adequate reflector system to direct the heat; an absorptive finish on the test specimen to permit maximum utilization of available heating power; a practical technique for surface temperature determination; a system of radiation measurement; and a computer control system to correctly vary the heat input to the test specimen.

II. SYSTEM LOGIC

Figure B-1 is a block diagram of the control system for the radiant heating test facility. Voltages analogous to h and t_{aw} are generated and then utilized by the computer along with a voltage analogous to t_s for solution of the Newtonian convective heat transfer equation, $q = h(t_{aw} - t_s)$. Another voltage (q_r) representing radiation from external sources (sun, atomic blast, etc.) is generated and then added to q in a summing circuit to give the desired heat flow signal, q_d . The comparator output, c , is the difference between q_d and q_m , the measured heat flow. The control signal causes the power regulating device to vary the power supplied to the heaters. The heat flow measurement system closes the control loop, causing the correct heat input to the test structure to be maintained. The measurement of heat input to the test specimen is made by either of two systems. The operational details of these devices are explained briefly in Section III and in detail in References [1] and [2].

III. SYSTEM DETAILS

Certain requirements are essential in a practical feedback control system for the simulation of aerodynamic heating. The requirements set for this facility are to:

- (1) accurately compute desired heat flows for simulation of speeds up to Mach 6.
- (2) be capable of measuring the heat inputs to the test specimen.
- (3) be dependable.
- (4) be safe to operate.
- (5) be inexpensive as possible.
- (6) be simple to operate and program.

The operations of the function generator and computer shown in Fig. B-1 are combined in the digital to analogue computer control system. This unit consists of a punched tape reader, an operational amplifier and resistance bank, two peak followers and associated capacitors, a multi-bank stepping switch, a summer, and a chopper stabilized amplifier. (Fig. B-2) The details of the individual components are given in Reference [1] and only the modus operandi is discussed here.

Values of h and t_{aw} are obtained from the Stefan-Boltzmann law. A binary coded program of these time dependent functions is made on a punched tape. This tape is placed on a reader and used in the time shared system as follows: an analogue voltage proportional to q_r is generated from a resistance network and a reference voltage in conjunction with an operational amplifier. This signal is temporarily stored. The next command is t_{aw} which is treated in the same way. The output of the temperature transducers, t_s , is amplified by a chopper stabilized amplifier and then subtracted from the stored t_{aw} analogue in a summer. The voltage difference $(t_{aw} - t_s)$ is used as the reference voltage for the next stage of the operation. This consists of giving the command, read h , and by virtue of the fact that the reference voltage is analogous to $(t_{aw} - t_s)$ the output of the system is analogous to the product $h(t_{aw} - t_s)$. Simultaneously, q and q_r are added in a summer and this voltage, analogous to q_d , is stored in a capacitor. These steps are repeated for channels two, three, and four. The digital to analog computer evaluates a new value of q_d for each channel every 1.2 seconds. Thus, by time sharing, by digital to analog conversion, and by unique computer techniques, [1] a simple and accurate means for obtaining a q_d history is realized.

There are two systems available for closing the control loop. Both systems measure the rate of heat flow to the test specimen and therefore may be used interchangeably. One system, the classic system, consists of special transducers. These essentially consist of thermocouples in conjunction with substantial heat sinks. In a radiant field the thermocouples reach an equilibrium temperature proportional to the radiant intensity. Each transducer is two thermocouples connected so that their signals oppose. One is subjected to the radiation from the heaters and the other to the reflected radiation. The output is therefore proportional to the difference between the incident and reflected radiation. This is q_m exclusive of convective losses. The heat sinks for the transducers are cooled metallic blocks. The instruments are attached directly to the sides of the heater arrays. They are calibrated in a calorimetric manner.

The other system, one especially devised for this project, consists of eighteen thermocouples arranged to obtain temperature profiles in the test specimen. A high speed stepping switch sequentially connects the thermocouple signals to an analogue computer which solves the appropriate heat flow equation. The computer is time shared by the 4 stations. The latter system is more versatile than the former since it measures net heat flow irrespective of the nature of the source. Thus convective losses in simulation are accounted for. An additional refinement to the computer permits compensation for radiant losses which the structure would normally experience in flight. Figure B-3 is a photograph of the feedback computer system.

Voltages in the control system are scaled such that at any time the prescribed q_d level is twice the anticipated q_m level. A summing circuit subtracts q_m from q_d and the output (c) is used to control the power regulating devices. Due to the two-to-one scaling the control signal consists of a set-point voltage plus an error voltage. Thus, the heaters are controlled in such a manner that the desired and actual heat inputs are equalized. This occurs when the error voltage level converges to zero and the control signal converges to the set-point voltage.

Main power is supplied through two 300 KVA, 480 volt, 3 phase, General Electric transformers. The power regulating devices consist of 75 KVA, 480 volt, 3 phase General Electric saturable core reactors and

their associated control units. Transient operation of the power equipment on an overload duty cycle makes possible peak outputs of two to three times rated value. Heating capacity of more than one megawatt is therefore feasible. Figure B-4 is a photo of the saturable core reactor units.

The basic heating elements are General Electric T.3 infra-red lamps. (See Fig. B-5) They consist of a tungsten filament supported by tantalum disc spacers in a sealed quartz tube $3/8$ of an inch in diameter and 12 inches in length. Each unit is rated at 1000 watts at 220 volts. They are capable of withstanding the 480 volt peak output of the power supply and under these conditions develop approximately 3 kilowatts.

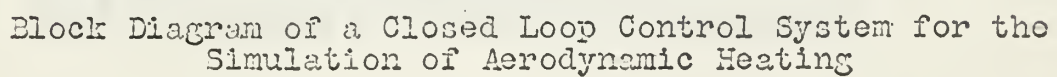
The heaters are arranged in groups of six. Figure B-6 is a photograph of one such unit. The heater arrays are connected in delta to the three phase power from the saturable core reactors. Each unit covers about one third of a square foot. Thus, the maximum radiant intensity possible with the present arrangement is about 60 kilowatts per square foot. Two thousand watt heaters of the same external size are available when higher intensities are required. Peak output of these is 6000 watts per heater. The heater arrays are quite adaptable and may be bolted to any suitable frame to surround a test structure. Special arrangements may easily be devised for special purposes, such as the heating of curved surfaces.

Figure B-7 shows an overall view of the test facility. The main items of equipment and the channels of information flow are outlined on the photograph. All control, computing and recording equipment is located in the control room. This room is on the second floor of the laboratory overlooking the test site. Large windows provide for visual observation of the structure under test. The remote location of the control room was dictated by safety considerations and provides a convenient, compact center for operation of the entire facility.

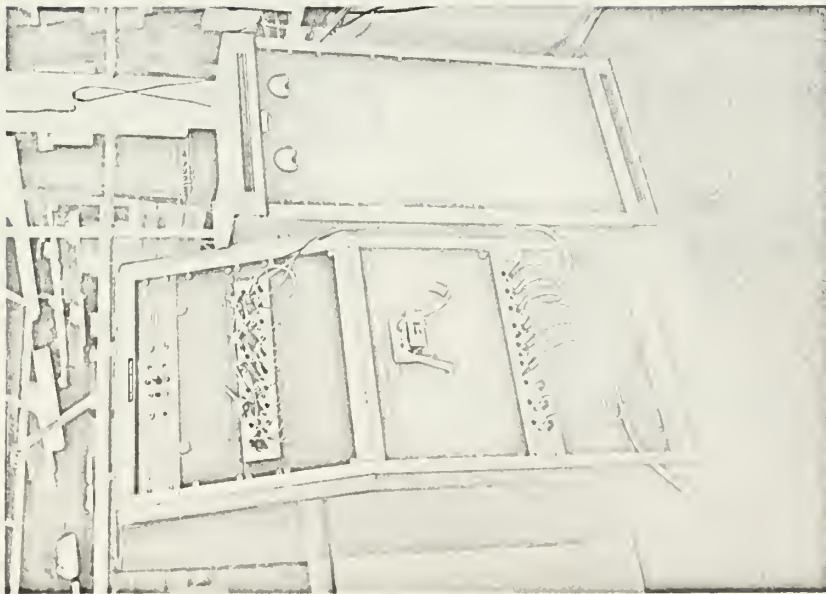
IV. CONCLUDING REMARKS

The design, construction, and operation of this test facility has proved that the concept of component time-sharing is practical in certain types of control systems. It is concluded that such time-sharing is an

economical proposition in which savings in equipment costs are balanced against slightly reduced system performance. The facility is such that it can be readily installed in any small research laboratory where cost is of prime importance.



- B-7 -



Digital to Analog Computer Control

Fig. B-2



Feedback Computer

Fig. B-3



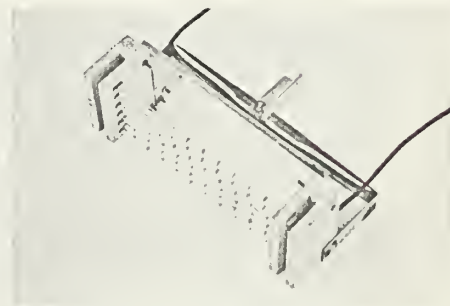
Saturable Core Reactors

Fig. B-4



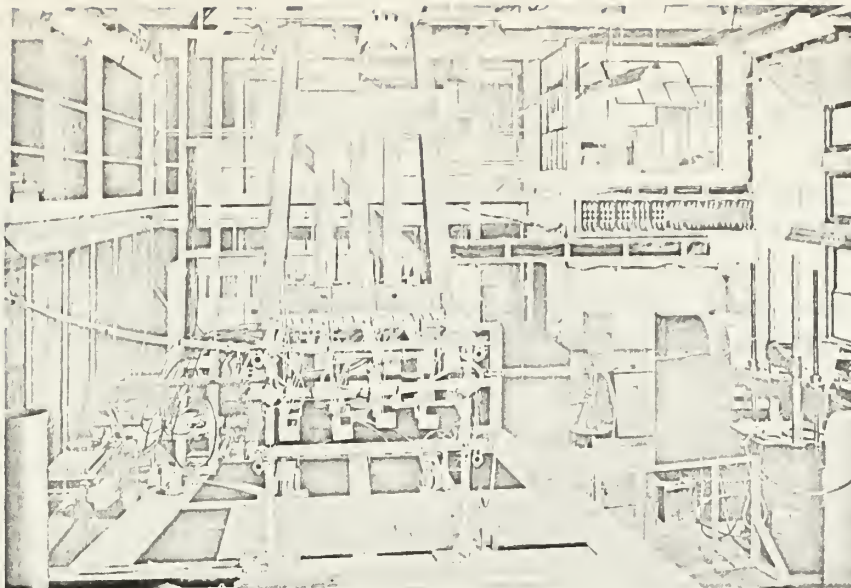
Infra-Red Heater

Fig. B-5



Heater Array

Fig. B-6



Overall View of Test Facility

Fig. B-7



Control Room

Fig. B-8

APPENDIX B REFERENCES

1. Geronime, E. L., A Digital-Analog Computer Control for Use in an Aerodynamic Heat Simulation System, Engineers Thesis, Stanford University, Stanford, California, 1962 August.
2. Campbell, J. D., A Feedback System for Automatic Control of Simulated Aerodynamic Heating, Engineers Thesis, Stanford University, Stanford, California, 1962 August.
3. Watson, R. M., A Heat Flow Measurement System, Engineers Thesis, Stanford University, Stanford, California, 1962 August.

APPENDIX C

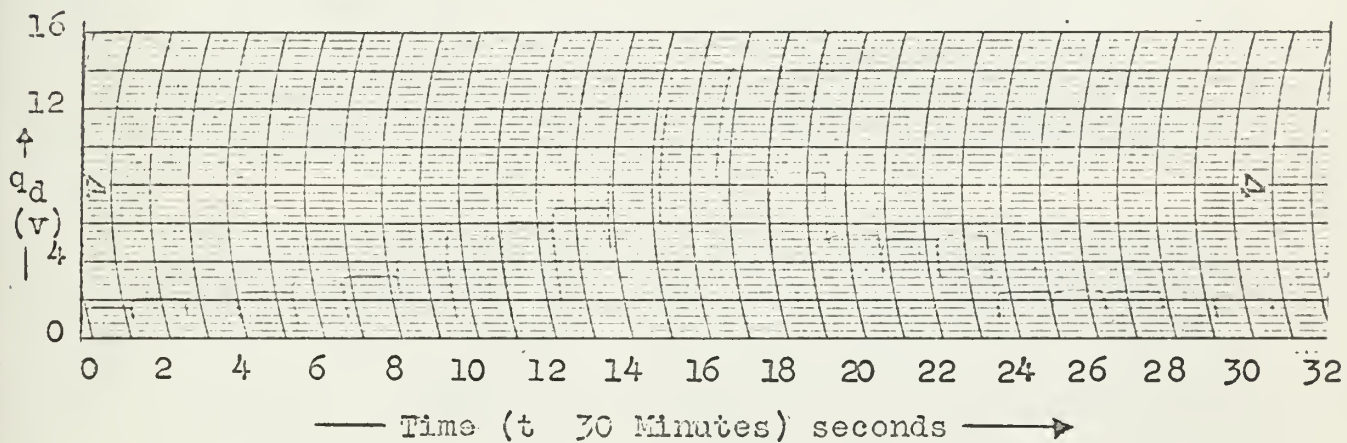
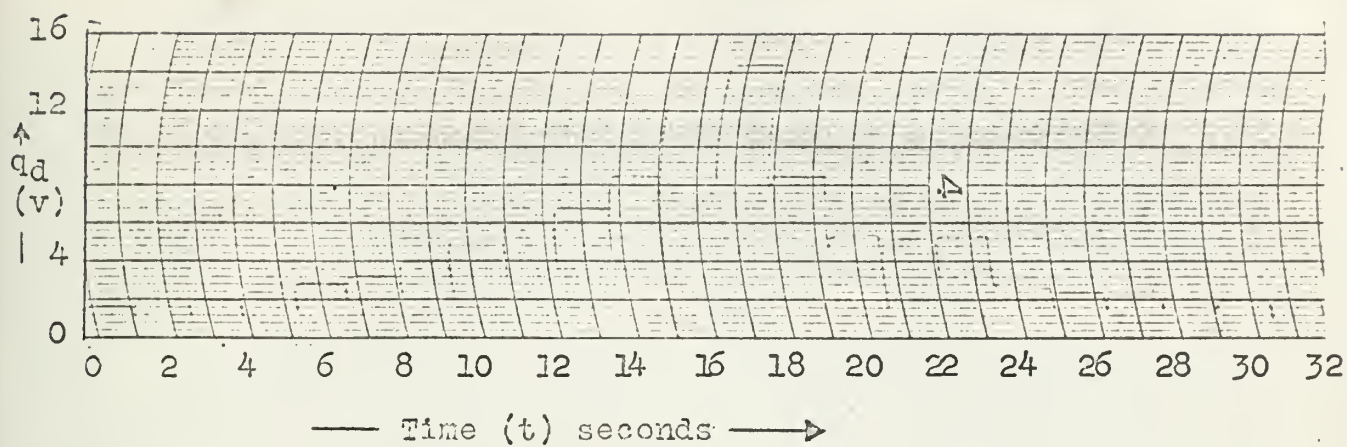
TEST DATA

TABLE I
DUPLICATION AND ACCURACY OF MULTIPLICATION

Reference Voltage	Multiplier	Actual Prod.	% Error
1.50 volts	3.60	5.35 volts	0.9
1.88 volts	3.60	6.70 volts	1.0
2.02 volts	3.10	6.26 volts	0.0
3.10 volts	3.10	9.60 volts	0.1
4.30 volts	3.00	12.7 volts	0.9
6.20 volts	3.00	18.3 volts	1.6
8.42 volts	2.95	24.4 volts	1.6
10.4 volts	2.95	30.3 volts	1.3
12.4 volts	2.60	32.0 volts	0.6
13.8 volts	2.60	35.3 volts	1.4
15.2 volts	2.20	33.8 volts	1.2
19.0 volts	2.20	42.1 volts	0.5

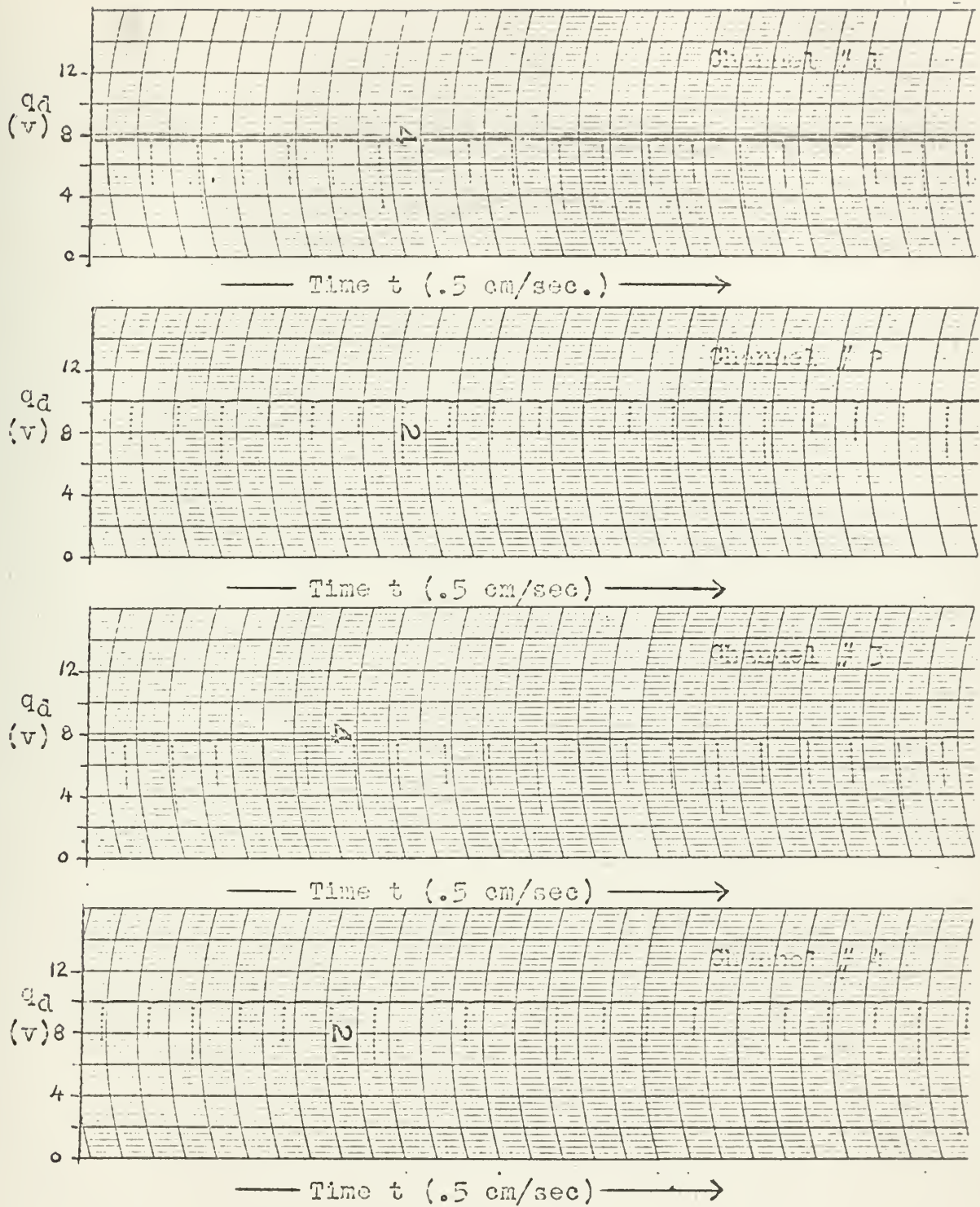
Duplication of Above Test after 15 Minutes:

1.50 volts	3.60	5.35 volts	0.9
1.88 volts	3.60	6.70 volts	1.0
2.02 volts	3.10	6.28 volts	0.3
3.10 volts	3.10	9.61 volts	0.0
4.30 volts	3.00	12.8 volts	0.8
6.20 volts	3.00	18.4 volts	1.0
8.42 volts	2.95	24.5 volts	1.0
10.4 volts	2.95	30.5 volts	0.6
12.4 volts	2.60	31.9 volts	1.0
13.8 volts	2.60	35.5 volts	0.8
15.2 volts	2.20	33.5 volts	0.3
19.0 volts	2.20	42.5 volts	1.4



A strip-chart recording of an arbitrary function
analogous to q_d starting at time t and at time $t+30$ minutes

Fig. C-1

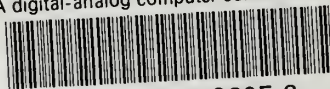


Strip-chart recording of constant q_d generated on each of four channels

Fig. C-2

thesG33

A digital-analog computer control for us



3 2768 002 02605 6

DUDLEY KNOX LIBRARY